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Measurements of Ocean Bottom Pressure with a Quartz Sensor*

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Abstract: Year long measurements of bottom pressure were made at 2,036 m depth in Sagami Trough, at 2,538 m depth in Suruga Trough, and at 32 m depth in the south of Minami-Daitojima Island. Amplitudes and phase lags of the major constituents of tides were estimated by the response method, and they were compared with the observational results at several tide stations operated by the Japan Meteorological Agency. A comparison with Schwiderski's global models for the eight tidal constituents showed that the amplitudes were in good accordance to one another within 3 cm, and that the differences of phase lags were less than 15°. The largest portion of the variations of the bottom pressure was caused by the tides: the variance of the major eight constituents was more than 98.5% as large as the total variance. The measurements show that tidal waves can be recorded offshore with a sufficient accuracy by the quartz sensors. Drifts of indication of the pressure gauges were significant and they prevented detection of a long-term variation which might be caused by fluctuations of the ocean currents or by the eddies.

1. Introduction

We have been carrying out long-term measurements of ocean bottom pressure in the Kuroshio region by using an Aanderaa Tide Gauge with a quartz sensor. The aim of the study is two-fold: to estimate amplitudes and phase lags of tidal waves in the open sea, and to detect a pressure variation which may be caused by fluctuation of the Kuroshio or by warm and cold eddies migrating over the observational stations.

Tide prediction for coastal waters has been accurate enough for practical purposes. Water levels at major ports and harbours in Japan are predicted on the basis of tidal constants, which are determined through long-term observation at each tidal station (Japan Meteorological Agency, 1984; Maritime Safety Agency of Japan, 1984). Recently, a satellite-borne instrument has changed the situation. A microwave altimetry has been proved to be most effective for monitoring positions and intensity of ocean currents or eddies (Wunsch and Gaposchkin, 1980). The current speed is proportional to the pressure gradient at the sea surface normal to the current direction, and the pressure gradient can be estimated from the altimetric data. One of the important missions of a Japanese satellite program (MOS, Marine Observation Satellite) is to monitor the path and surface intensity of the Kuroshio with a microwave altimeter. Accuracy of measurements is presently about 10 cm, and the accuracy of several centimeters is expected to be achieved in the near future. In order to derive instantaneous features of the current fields, one needs to estimate the water level due to tides with a sufficient accuracy (Schwiderski and Szeto, 1982). For an accuracy of 10 cm, the amplitude of each constituent must be determined at least with an error less than 5 cm. When an amplitude is 50 cm, the phase lag must be determined with an error less than 11.5° (=arcsin 0.2).

The amplitude and phase of tidal waves propagating in the open sea are determined through solving the tidal equations. Schwiderski (1979, 1981a, 1981b, 1981c, 1981d, 1981e, 1981f and 1981g) tabulated the amplitudes and phase lags of eight major constituents of tides, M2, S2, K1, O1, N2, P1, K2 and Q1 on each 1°×1° grid over the whole oceans. Tidal constants at more than two thousand shore stations and thirty-two offshore stations were used

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as boundary conditions for the hydrodynamic model for each constituent. Schwiderski showed that the models gave amplitudes with a difference less than 4 cm and phase lags with a difference less than 10° for these offshore stations. Unfortunately, there was no direct measurement of offshore tides in the northwest Pacific west of 145°W. A comparison of the direct measurements with the models has been requisite in this sea area. Ocean bottom pressure has been measured with pressure sensors of various principles (Isozaki *et al.*, 1980). Since 1978, a pressure gauge with a quartz sensor has been kept at 2,200 m depth off Omaezaki for warning of tsunami, and tidal constants at the station have been published (Meteorological Research Institute, 1984).

Wearn and Baker (1980) discussed the variations of transport across the Drake Passage by measuring the pressure gradients on the bottom with a depth of about 500 m. Taira and Teramoto (1981) showed that the velocity fluctuations with a period of 30 day was of magnitude of 20 cm sec^{-1} at 1, 700 m depth under the Kuroshio path east of Hachijojima Island. Hydrographic casts in the cold water mass accompanied with a steady meander of the Kuroshio path show that the water temperature at more than 3, 000 m depth is still lower than that of the surrounding water. These may suggest that a long-term variation of bottom pressure can be detected at deep layers under the Kuroshio path.

Observational results at 2, 036 m depth in the Sagami Trough, at 2, 538 m depth in the Suruga Trough, and at 32 m depth in the south of Minami-Daitojima Island. (hereafter referred as Daito) are described in this paper. The former two were located under the Kuroshio path, and tidal constants at nearby shore stations were known. Daito was selected because it was located about 360 km away from the nearest tide stations. Nominal accuracy of the pressure sensor used in this study is too crude to measure the offshore tides as described later. An intercomparison with nearby shore stations is required to examine the practical accuracy of the sensor.

2. Instruments and observations

We adopted an Aanderaa Tide Gauge with a quartz sensor manufactured by Paroscience Inc. The absolute pressure is detected and recorded internally on a magnetic tape at a selected time interval. Repeatability and hysteresis are 0. 005% of the full scale of the sensor. For a sensor of 34. 5 MPa full scale, they are 17. 2 hPa. Null stability over six month is guaranteed to be less than 0. 008% of the full scale, or 27. 6 hPa for the sensor. Temperature null shift is 0. 0007 %/°C. Recording resolutions are 2. 3 hPa. We used a pressure gauge with the 6. 2 MPa for the measurement at Daito, and the recording resolutions are 0. 4hPa for the gauge. A quartz-

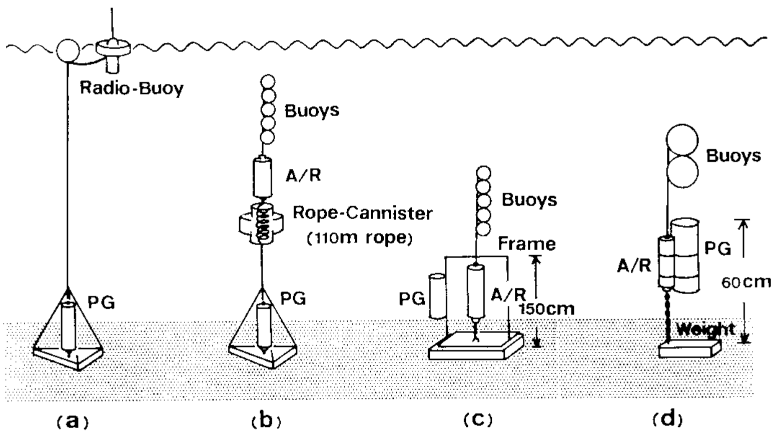

Fig. 1. Schematics of the moorings for the bottom pressure measurements: (a) a mooring with surface buoys, (b) a mooring with a rope cannister, (c) a mooring with a mounting frame, and (d) a simple mooring. The method (c) was applied to SG-I, SG-II and SR, and (d) to Daito.

Table 1. Data regarding the moorings for the pressure gauges.

Station	SG-I	SG-II	SR	Daito
Latitude	34°43′N	34°43′N	34°12′N	25°49′N
Longitude	139°39′E	139°40′E	138°40′E	131°13′E
Period of observation	26 Feb 1983- 7 Jun 1983	7 Jun 1983- 16 May 1984	3 May 1983- 24 May 1984	13 Oct 1983- 11 March 1984
Duration	102 days	344 days	388 days	151 days
Mean presssure	20. 59 MPa (2099. 7 mH_2O)	19. 98 MPa (2037. 0 mH_2O)	25. 65 MPa (2616. 0 mH_2O)	0. 32 MPa (32. 6 mH_2O)
Full scale of gauge	34. 5 MPa	34. 5 MPa	34. 5 MPa	6. 2 MPa

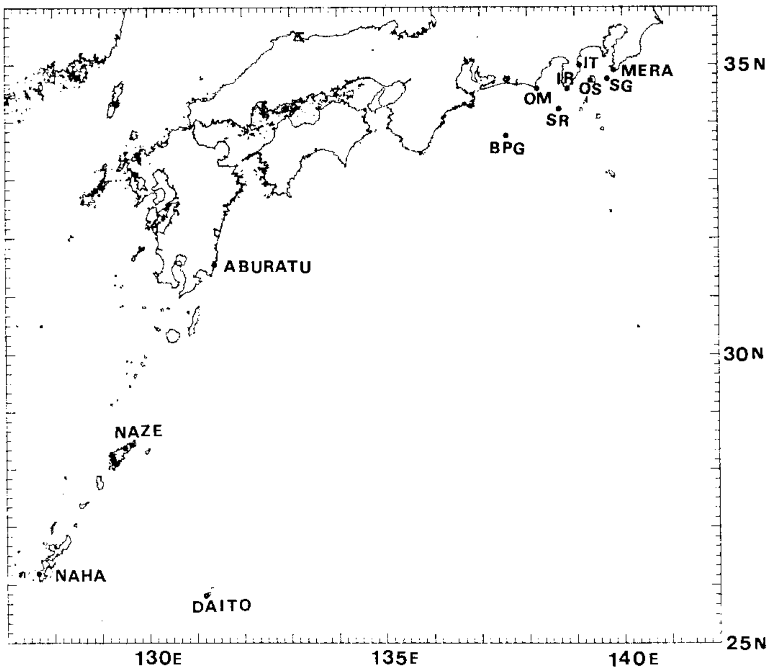

Fig. 2. Map of the study area. The mooring stations of the pressure gauges: Sagami Trough (SG), Suruga Trough (SR), and Minami-Daitojima (Daito). Referred tide stations: Mera, Oshima (OS), Ito (IT), Omaezaki (OM), Aburatu, Naze, Naha, and the bottom Pressure Gauge off Omaezaki (BPG). Meteorological Observatories: Oshima (OS), Irozaki (IR), and Minami-Daitojima (Daito).

thermometer is installed in the pressure case. Recording interval of 1 hr was selected for the present study.

Mooring technique is important because the pressure gauge must be mounted rigidly on the sea floor. In 1976, we made moorings with surface buoys as shown in Fig. 1a at 40 m depth in Otsuchi Bay (Taira *et al.*, 1977) and at 190 m depth on the western slope of the Izu Ridge. This method cannot be applied for the long-term measurements nor to the deep seas. In 1977, we made a bottom mooring by using a rope cannister as shown in Fig. 1b in the northern part of Sagami Bay and obtained forty-day long record. This method cannot be applied for the deep seas. In 1983, we invented a bottom mooring device as shown in Fig. 1c. This method can be adopted both for deep seas and for long-term measurements. We have recovered the bottom mooring of this method four times without any failures.

The bottom pressure measurements in Sagami Trough (SG-I and SG-II), Suruga Trough (SR) and Minami-Daitojima (Daito) are described in this paper (Table 1). The bottom mooring devices (Fig. 1c) were used for SG-I, SG-II and SR. A simple mooring (Fig. 1d) was adopted for Daito. The mooring stations are shown in Fig. 2.

Tidal analysis was made by the response method (Ooe and Sato, 1983). Amplitudes and phase lags (*k*, the local equilibrium arguments) of the major eight constituents were compared with the observational results at shore stations of the Japan Meteorological Agency, and with those computed by Schwiderski's global models.

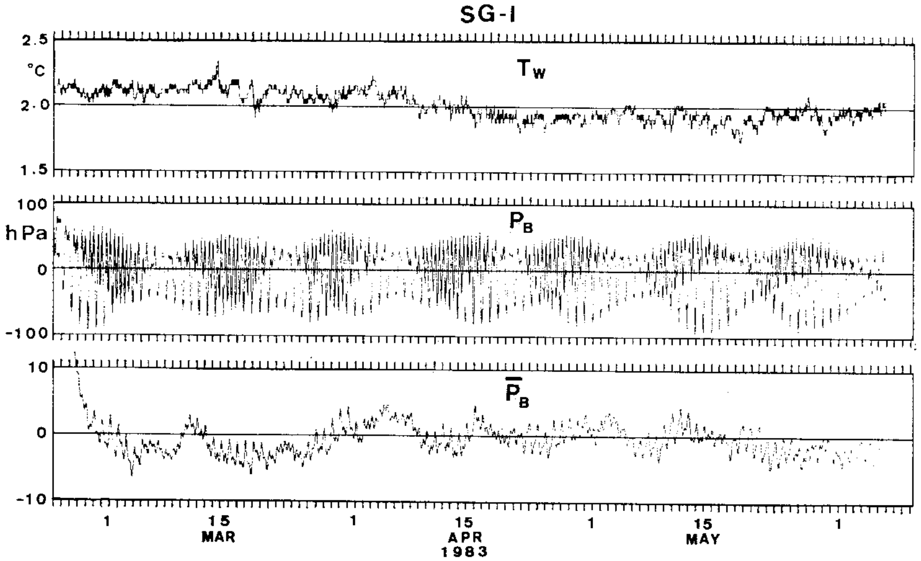

Fig. 3. Recorded time series in the Sagami Trough of Temperature (T_W), bottom pressure (P_B), and the 25-hr averaging of the bottom pressure ($\bar{P}_B$).

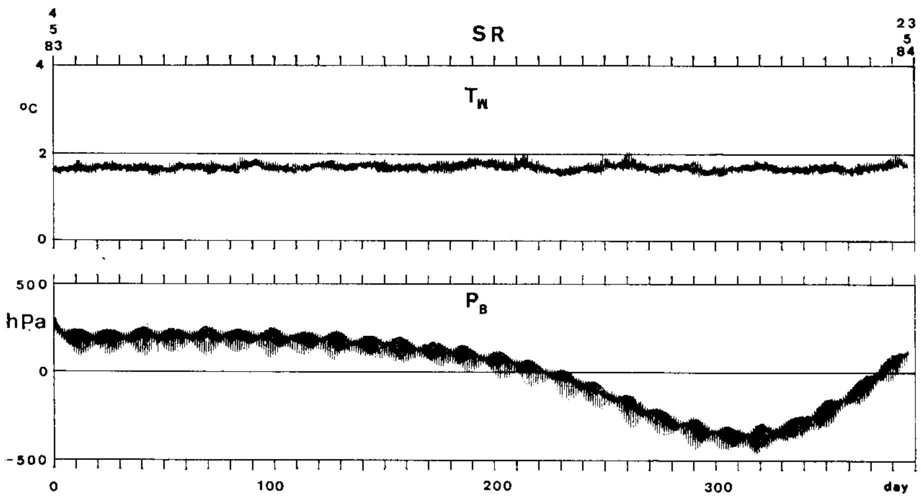

Fig. 4. Recorded time series in the Suruga Trough of Temperature (T_W), bottom pressure (P_B), and the 25-hr averaging of the bottom pressure ($\bar{P}_B$).

Daily means of atmospheric pressure at Oshima and Irozaki (Japan Meteorological Agency, 1983) were compared with the bottom pressure in Sagami Trough and Suruga Trough, respectively. Atmospheric pressure at every hour was read from the barometric charts of the Minami-Daitojima Local Meteorological Observatory, which is about 2 km away from the observational station of the bottom pressure.

3. Analysis of tides

Figure 3 shows water temperature (T_W), bottom pressure (P_B), and its averaging over 25 hr ($\overline{P}_B$) observed in the Sagami Trough (SG-1), Variation of the temperature was less than 0.5°C. Strong tidal signals dominate in the record of the bottom pressure. The 25h-averaged pressure ($\overline{P}_B$) shows that the pressure decreases rapidly from a larger value in four days after the deployment; an overshoot is occurred for the pressure sensor.

Figure 4 shows water temperature and bottom pressure observed in Suruga Trough (SR). Variation of the temperature was less than 0.5°C. A large drift dominates in the record of the bottom pressure. Recovery from the overshoot occurred within five days after deployment. The bottom pressure was nearly constant for the first 100 days, and then it decreased rapidly. After it reached to a minimum value on the 310-th day, it increased rapidly until the end of the record. The tidal signals dominate in the record.

Figure 5 shows water temperature, bottom pressure and atmospheric pressure at Minami-Daitojima (Daito). Temperature was decreasing largely from a maximum of 28.5°C in the early October to a minimum of 20°C in the early March. Temperature measured in the pressure case was considered to be representing the temperature of the surrounding water with a certain time delay. The bottom pressure was high for almost 30 days in the beginning of the measurements. Strong tidal signals dominate in the record.

We estimated tidal constants from the 100 day long records for SG-1 and Daito, and the 50 day long record for SR by avoiding the portions of the overshoots and large trends. The results of the analysis are tabulated for the major eight constituents in Table 2.

A composite of eight tidal constituents was calculated, and the difference between the observed bottom pressure and the composite was compared with the variation of the atmospheric pressure. Figure 6 shows the observed bottom pressure, the composite, and the difference between them for the 100-day long record in the Sagami Trough, and the daily-mean atmospheric pressure at Oshima for the period. The bottom pressure and the composite are very similar to one another. The standard deviation of the difference between them is 3.3 hPa, which is 1.4 times as large as the recording resolution. The variance of the difference is 10.6 $(hPa)^2$. On the other hand, the variance of the atmos-

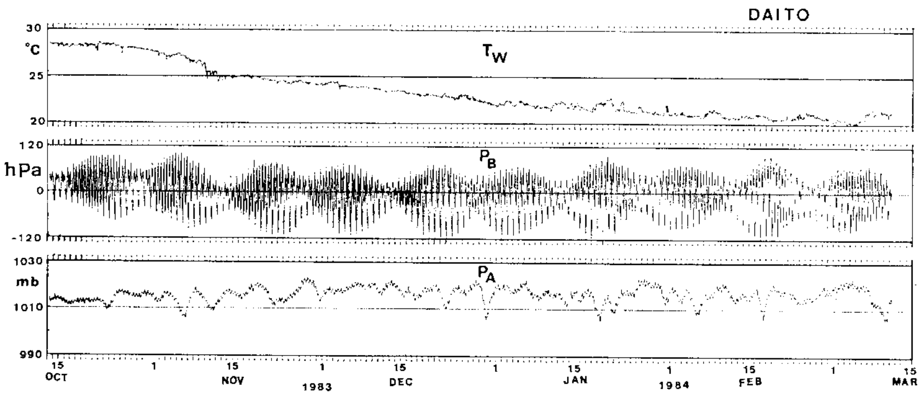

Fig. 5. Recorded time series at Minami-Daitojima (Daito) of temperature (T_W), and bottom pressure (P_B). The bottom panel shows the hourly record of atmospheric pressure observed at the Minami-Daitojima Local Meteorological Observatory.

Table 2. Amplitudes (in cm) and phase lags (the local equilibrium arguments, in degree) of eight major constituents of tides determined from the ocean bottom pressure measurements. The mean density of sea water is taken to be 1.03 g cm^{-3} for SG-I and SR, and 1.02 g cm^{-3} for Daito. The values predicted by Schwiderski's model, and their differences are shown in the parentheses. Variances of the bottom pressure, the difference between the total pressure and the composite of eight constituents, and the atmospheric pressure are tabulated in the bottom lines.

Station		SG-I	SR	Daito
Period of analysis		26 Feb 1983 - 5 June 1983	14 July 1983 - 1 Sept 1983	13 Nov 1983 - 20 Feb 1984
Duration		100 days	50 days	100 days
M2	Amplitude	33.8 (35, 1)	39.3 (38, −1)	52.2 (55, 2)
	Phase lag	144.1 (149. 5)	165.2 (159, −6)	189.8 (197, 7)
S2	Amplitude	15.9 (18, 2)	18.1 (18, 0)	22.5 (23, 0)
	Phase lag	175.2 (171, −4)	192.8 (185, −8)	214.0 (222, 8)
K1	Amplitude	23.9 (23, −1)	21.2 (22, 1)	18.7 (21, 2)
	Phase lag	176.0 (177, 1)	183.7 (181, −3)	201.8 (206, 4)
O1	Amplitude	18.6 (19, 0)	16.4 (18, 2)	14.7 (15, 0)
	Phase lag	157.7 (159, 1)	166.5 (161, −6)	184.5 (186, 1)
N2	Amplitude	4.6 (5, 0)	10.0 (7, −3)	9.8 (10, 0)
	Phase lag	148.7 (149, 0)	150.3 (165, 15)	182.4 (189, 7)
P1	Amplitude	7.8 (7, −1)	6.8 (7, 0)	6.2 (6, 0)
	Phase lag	175.3 (180, 5)	178.8 (182, 3)	201.2 (209, 8)
K2	Amplitude	4.5 (4.7, 0)	5.2 (5.1, 0)	6.2 (6.4, 0)
	Phase lag	164.3 (177, 13)	188.9 (188, −1)	210.2 (223, 13)
Q1	Amplitude	3.6 (3.8, 0)	4.0 (3.8, 0)	3.4 (3.0, 0)
	Phase lag	148.2 (153, 5)	152.9 (153, 0)	173.7 (176, 2)
VAR (P_B)		1183.4 (hPa)^2	1309.1 (hPa)^2	2065.6 (hPa)^2
VAR (P_B-P_C)		10.6 (hPa)^2	15.7 (hPa)^2	30.8 (hPa)^2
VAR (P_A)		50.5 (hPa)^2	31.2 (hPa)^2	9.1 (hPa)^2

pheric pressure is 50.46 (hPa)^2. This shows that the variation of the atmospheric pressure scarcely arrives to the deep bottom. A balance between the water level and the atmospheric pressure variation is considered to be realized so that the pressure variation on the deep bottom is minimized. Spectral analysis was made by the method of Blackman and Tukey (1958). The power spectrum of atmospheric pressure at Oshima had a spectral peak at 1/206 cph (cycle per hour). The spectrum of the difference (P_B-P_C) had spectral peaks at 1/12.5, 1/25.0 and 1/200 cph.

Figure 7 shows the observed bottom pressure, the composite of eight constituents, and the difference between them for the 50-day long record in the Suruga Trough, and the atmospheric pressure at Irozaki. Similarity between the observed and the composite pressure is very high, and the difference between them reveals that the trend is significant. The total variance of the difference is 59.4(hPa)^2, but it decreases to 15.7(hPa)^2 when the variance with frequencies lower than 1/100 cph is removed.

Figure 8 shows the observed bottom pressure, the composite of the eight constituents, and the difference between them for the 100-day long record at Daito, and the atmospheric pressure at Minami-Daitojima. Variance of the difference is 30.8(hPa)^2, and that of the atmospheric pressure is 9.1(hPa)^2. Autocorrelation function of the atmospheric pressure had the first zero crossing at 86 hr, which indicated a periodicity of 14 day. The autocorrelation function of the difference (P_B-P_C) had no zero crossing. Coherency between the atmospheric pressure and the difference was lower than 0.5. The standard

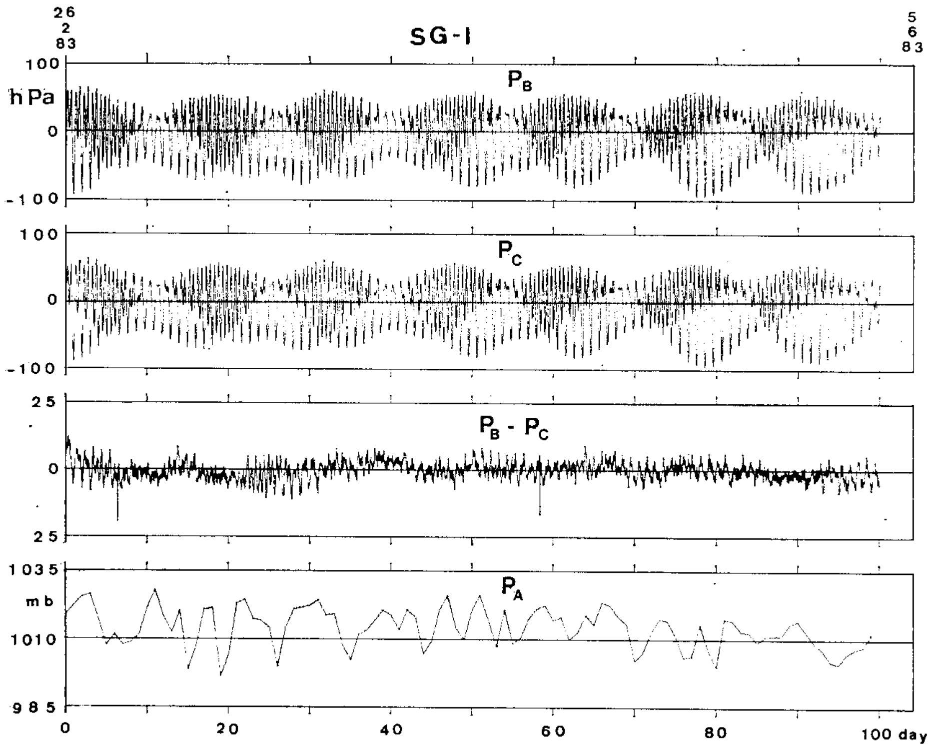

Fig. 6. Bottom pressure in the Sagami Trough for 100 days of the tidal analysis (P_B), a composite of the eight major tidal constituents (P_C), and the difference between them (P_B–P_C). The bottom panel shows the daily-mean record of atmospheric pressure at the Oshima Meteorological Observatory.

deviation of the difference is 5.7hPa, which is 15 times as large as the recording resolution. The large deviation was considered to be caused by the depth change of the pressure gauge. The pressure gauge was to be lowered by 5.7 cm when the mooring line was inclined by 25 from the vertical due to the drag of currents (see Fig. 1d). The motion of the pressure gauge was considered to be responsible for the fluctuations of the record.

4. Long-term variations

The stations in Sagami Trough and Suruga Trough were selected in order to examine fluctuations of bottom pressure, which might be associated with the velocity fluctuations in the Kuroshio as reported by Taira and Teramoto (1981). We obtained continuous records of 445 day length for the former (SG-I and SG-II) and 388 day length for the latter (SR). The position of the SG-II was about 1 km east of the SG-I (Table 1). Figure 9 shows the daily values averaged over 25 hr for these stations.

Response characteristics of three pressure sensors were different from each other. The overshoot of the indication occurred at the time of deployment for the SG-I and the SR. The overshoot for the SG-II occurred slowly and a maximum was recorded two days after the deployment. The overshoot lasted for about 20 days for the SG-II. On the other hand, the overshoot lasted for less than five days both for the SG-I and the SR. The large trends were observed both for SG-II and SR. The pressure values of the SG-II were increasing linearly after the overshoot. The null shifts for SG-I and SG-II were smaller than the guaranteed value of 27.6 hPa except the overshoots. The null shifts of the sensor for the SR was remarkable as described previously. The magnitude was

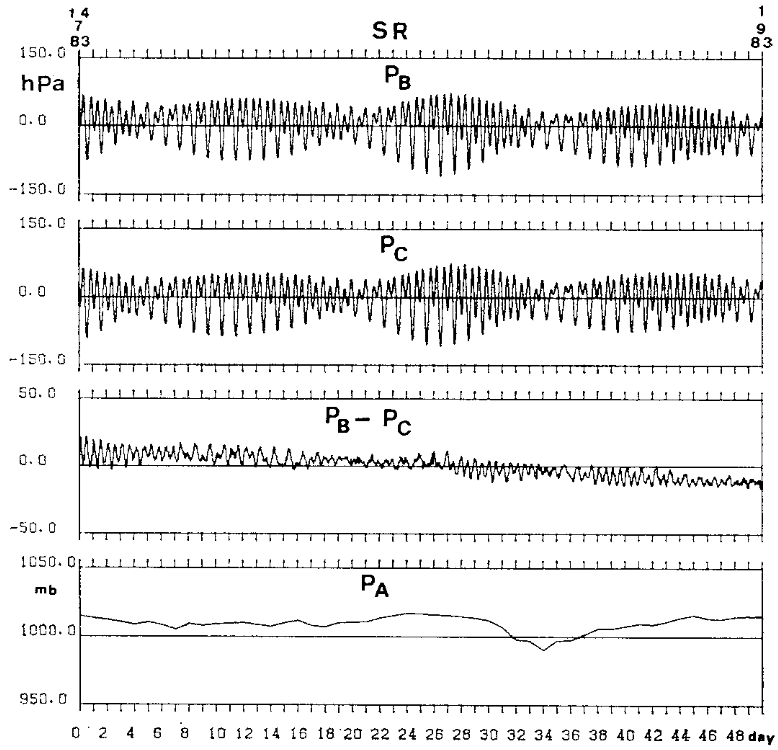

Fig. 7. Bottom pressure in the Suruga Trough for 50 days of the tidal analysis (P_B), a composite of the eight major tidal constituents (P_C), and the difference between them (P_B-P_C). The bottom panel shows the daily-mean record of atmospheric pressure at the Irozaki Meteorological Observatory.

550 hPa, which was twenty times as large as the guaranteed value. Provided that the pressure gauge had functioned properly, a movement of the mooring along the sea floor or terrestrial rise and fall might be suggested.

These results suggest that monitoring of long-term fluctuations associated with oceanic changes can be made hardly with the pressure gauges moored at a great depth. The recorded bottom pressure was mainly due to the tides. The residua were small: their variances were 0.9% of the total for SG-I, 1.2% for SR, and 1.5% for Daito as shown in Table 2. We abandoned a further analysis of the long-term fluctuations in the records obtained in Sagami Trough and Suruga Trough.

The overshoot of the sensor moored at Daito was about 2 hPa, and it lasted for two days. Figure 5 shows that the sea level was high for the first 30 days. We found a good correlation between the daily-mean pressure and the water temperature. Figure 10 shows the 25 hr averaging values of pressure plotted against the temperature. The temperature decreased from 28.5°C to 25.5°C, while the bottom pressure decreased by 30 hPa in the 30 days. The pressure decrease was ten times as large as the temperature shift of the sensor, and the decrease was considered to be significant. The water level will be lowered by 30 cm when the temperature decreases by 3°C at the upper 300 m layers of the ocean. When the pressure gauge is set at an upper layer, the change of water level will be recorded as a decrease of the bottom pressure. The linear correlation between the pressure and the temperature was lost after 15 November.

5. Discussion

The tidal constants estimated for the Sagami Trough, the Suruga Trough and Minami-Daito-

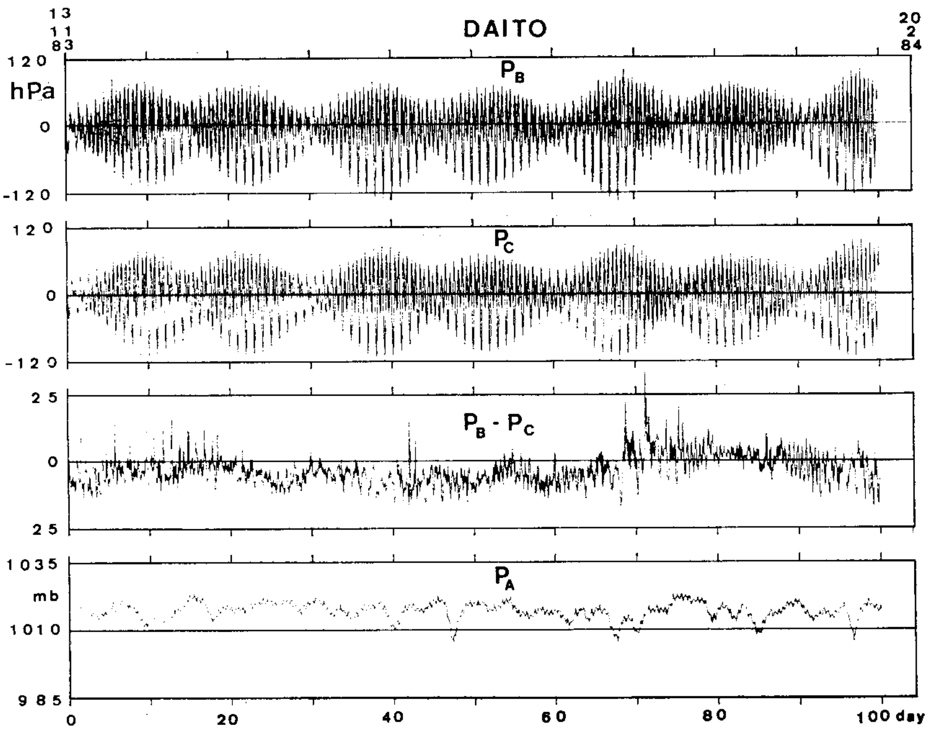

Fig. 8. Bottom pressure at Daito for 100 days of the tidal analysis (P_B), a composite of the eight major tidal constituents (P_C), and the difference between them (P_B-P_C). The bottom panal shows the hourly record of atmospheric pressure at the Minami-Daitojima Local Meteorological Observatory.

jima Island are compared with observational re by the Japan Meteorological Agency (1984). Figure 11 shows amplitudes and phase lags for the major four tidal constituents. Tidal constants were determined from the bottom pressure measurements at four stations, SG, SR and Daito of this study, and BPG (Bottom Pressure Gauge off Omaezaki; Meteorological Research Institute, 1984). The amplitudes from the pressure measurements were converted by taking the mean density of sea water to be 1.02 g cm^{-3} for Daito and 1.03 g cm^{-3} for the remaining stations.

Phase lags in Fig. 11 show that the tidal waves are propagating from east to west. Phase lags of the semidiurnal tides at Aburatu are somewhat smaller, indicating a southward propagation of the tides. From this point of view, the phase lag at Naze seeems to be rather larger than the value estimated from those at southern stations of Daito and Naha. The amplitudes of the semidiurnal tides are increasing westwards. The amplitudes of the diurnal tides increase from Mera to SG, and then decrease westwards. The comparison shows that the tidal observations with the pressure gauges mounted on the deep bottom are as accurate as those at shore tide stations.

The observational results of the present study were compared with the computational results by Schwiderski (1979, 1981a, 1981b, 1981c, 1981d, 1981e, 1981f and 1981g). Table 2 shows the amplitudes and phase lags of the present study, those by Schwiderski's models, and the differences between them. The difference of the amplitudes is less than 3 cm in the all cases. The differences of phase lags are less than 15°. Tidal constants computed by the models are given on each grid of one degree length of both longitude and latitude. A grid-to-grid difference of amplitudes is less than 3 cm in our study area. We conclude that the observed amplitudes are in good accordance with those com-

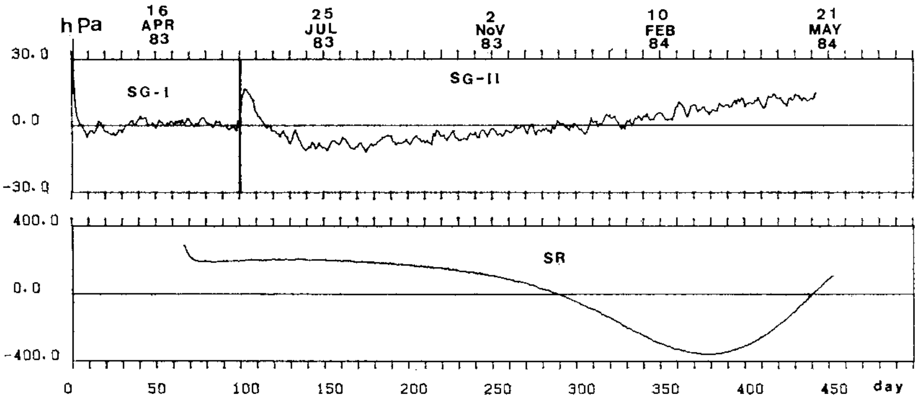

Fig. 9. The 25-hour averaging of the bottom pressure in the Sagami Trough (upper) and in the Suruga Trough (lower).

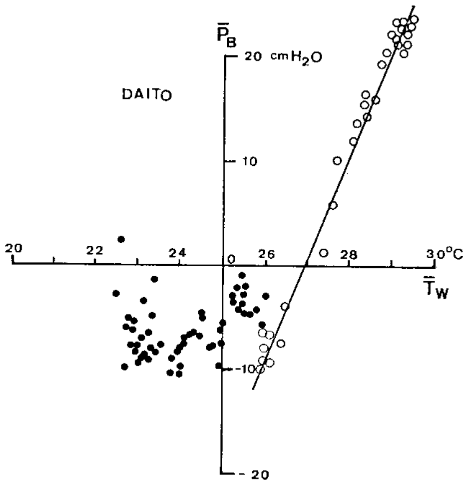

Fig. 10. Correlation diagram between the bottom pressure and the water temperature observed at Daito. Daily values are calculated by averagingover 25 hr. Circles show the values for the 30 days from 15 November to 14 November 1983, and dots for 70 days from 15 November 1983 to 21 February 1984. A linear curve shows the relation of 10cmH$_2$O/°C, or 9.8hPa/°C.

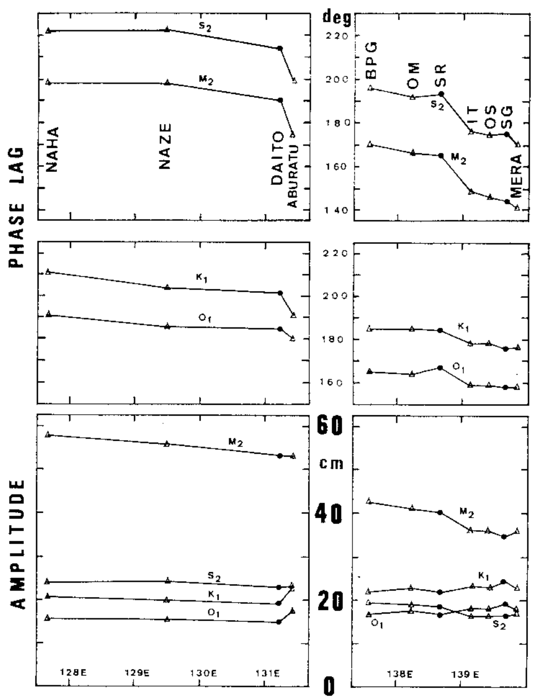

Fig. 11. Comparison of phase lags and amplitudes of the four major constituents observed by the bottom pressure gauges with those observed at shore tide stations. Names of the stations are shown in Fig. 2.

puted by the models. The maximum grid-to-grid differences of the computed phase lags for the M2 are 23° at the SG, 12° at the SR and 5° at the Daito. The phase differences between the observed and the computed are smaller than the grid-to-grid differences. The comparison reveals that Schwiderski's model describes well the tides in the study area with a high accuracy. We expect that further observations of offshore tides and a local model of tides can provide prediction of sea level with much higher accuracy in the Kuroshio area west of the Izu Ridge.

6. Summary

The results of this study can be summarized in three main conclusions. (1) The tidal constants were determined from the offshore measurements of the bottom pressure at the depths of 32 m, 2,036 m and 2,538 m. The comparison shows that the tidal constants determined from the pressure measurements are as accurate as those from the measurements of water level at shore tide stations. (2) The comparison of the tidal constants of the present study with those computed by Schwiderski shows that the amplitudes are in good accordance with a difference less than 3 cm and that the differences of phase lags are less than 15°. (3) Variance of the bottom pressure was mainly due to the tides: the variance of the eight major constituents was more than 98.5% as large as the total. The sensors of a large full scale (34.5 MPa) had the overshoots and the null shifts during the observations, and a pressure variation associated with fluctuation of the Kuroshio was not significant.

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水晶圧力計による海底圧力の観測

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要旨: アーンデラ水晶圧力計を用いて，相模トラフの2,036 m 水深点，駿河トラフの 2,538 m 水深点，そして南大東島沖の 32 m 水深点で海底における水圧変動の通年観測を行なった．潮汐の各分潮の振幅と位相を応答法を用いて評価した．気象庁の沿岸観測値との比較によって，水晶圧力計による潮汐の観測精度が十分に高いことがわかった．Schwiderski (1979, 1981) の潮汐の全球モデルの計算結果と，主要8分潮について比較し，振幅は 3 cm 以内，位相は 15° 以内で一致することがわかった．海底圧力の変動は潮汐が卓越していて，主要8分潮を除いた剰余の分散は，もとの分散の 1.5% 以下であった．圧力計の指示値のドリフトのため，海流の変動や渦の移動によって生ずると思われる長周期変動の解析はできなかった．

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